Results and perspectives of forward physics in ATLAS

Benedetto Giacobbe

On behalf of the ATLAS Collaboration

Cosmic Ray International Seminar
14-16 September 2015, 2015 Gallipoli, Italy

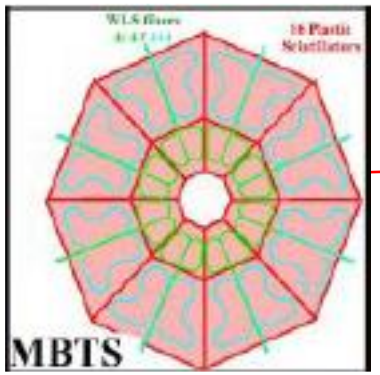
outline

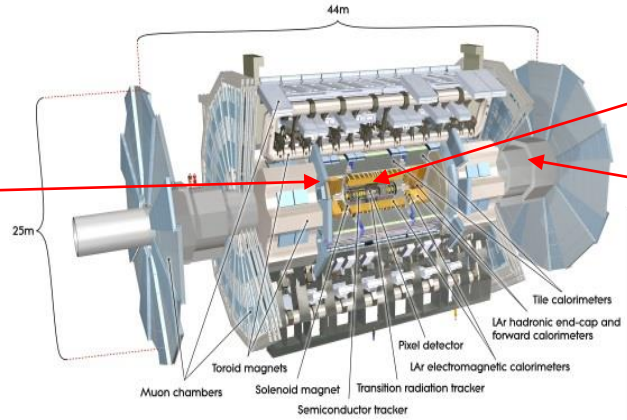
- The ATLAS Forward Detectors
- The ATLAS program of pp cross section measurements @ 7 TeV
  - Inelastic cross section
  - Total and elastic cross section (using proton tag)
  - Differential inelastic cross section (using rapidity gaps)
- Inelastic cross section measurement at 13 TeV

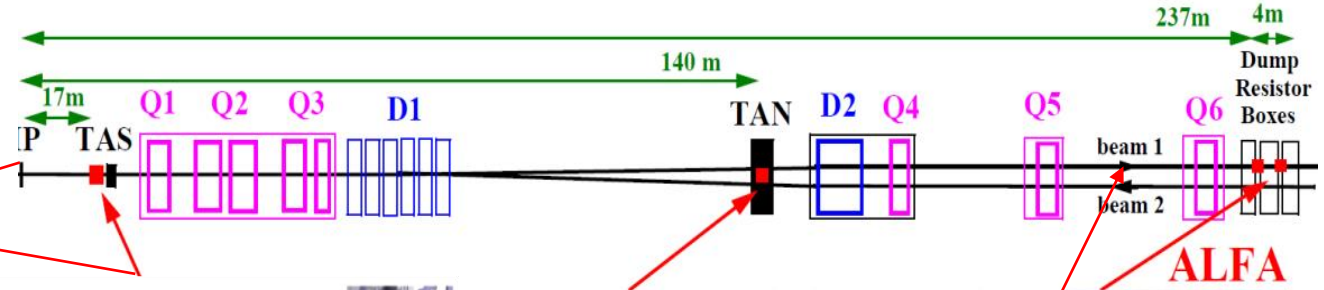
new!

- Transverse energy flow in the forward direction
- Future perspectives
  - ATLAS Forward Physics (AFP)
  - Total cross section at higher energy (and lower |t|)

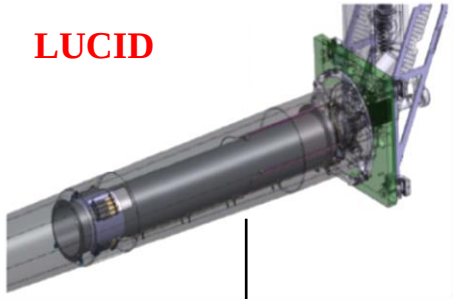
The ATLAS Forward Detectors



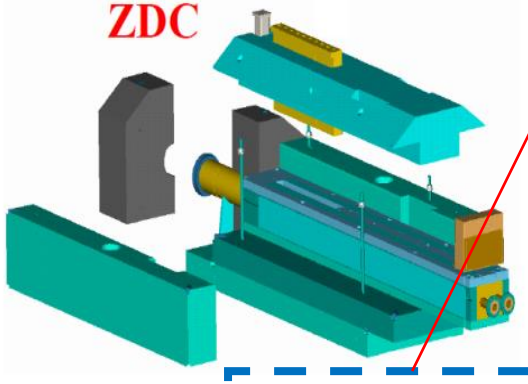




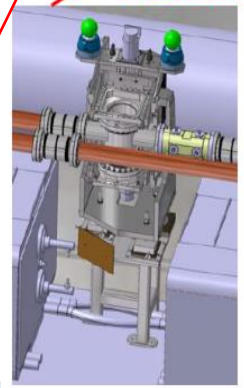
LUCID



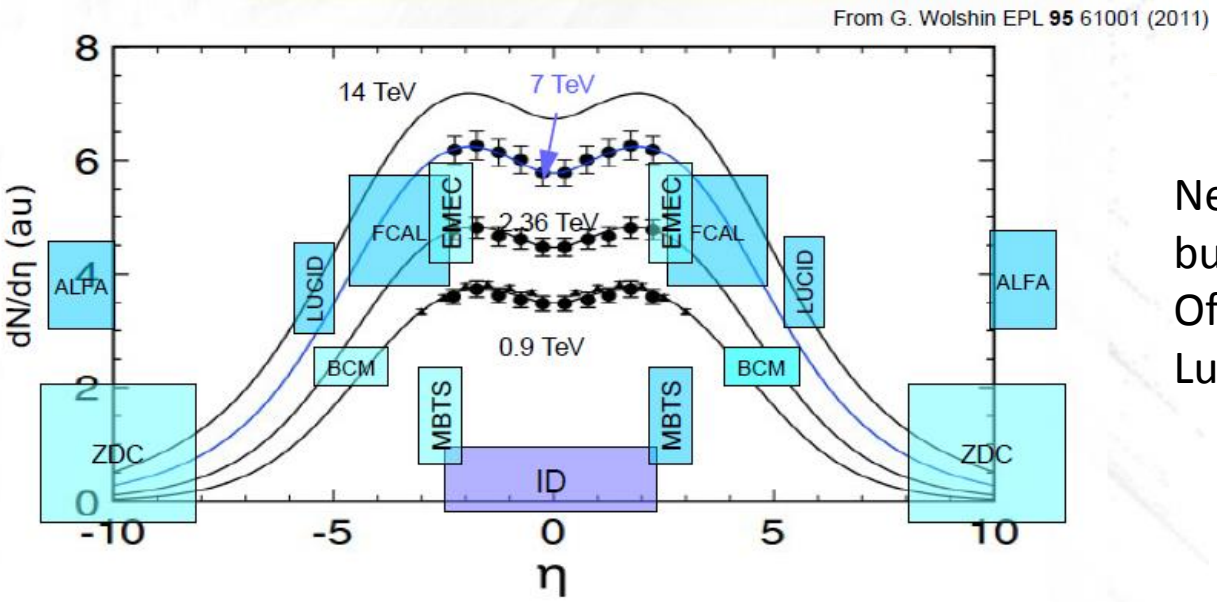
ZDC



ALFA

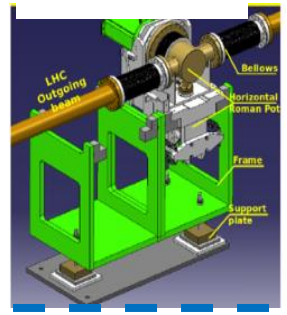


Since 2011



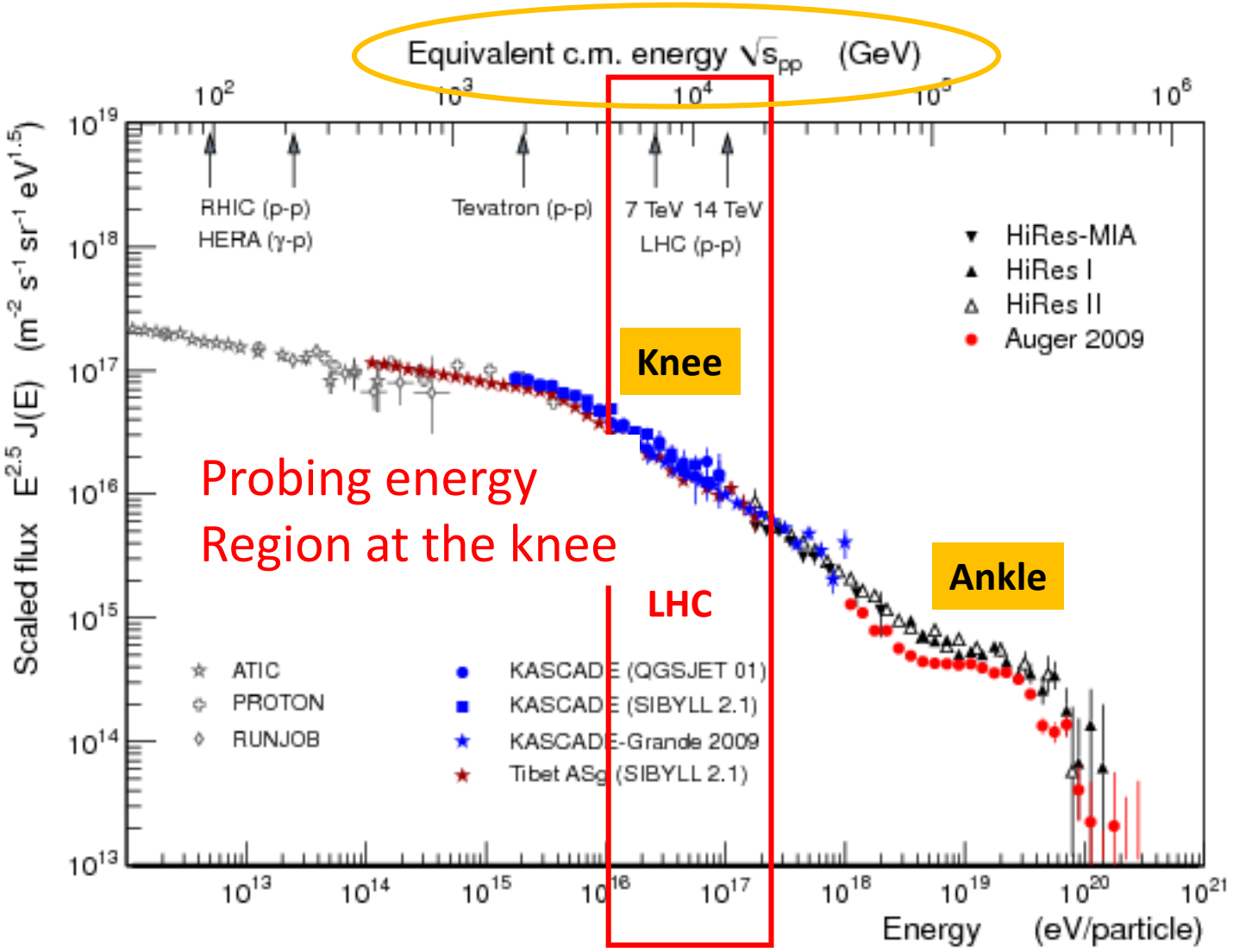
New detector built for Run 2. Official ATLAS Luminosity monitor

AFP



To Be installed from 2015-2016

Where is LHC compared to cosmic rays ?

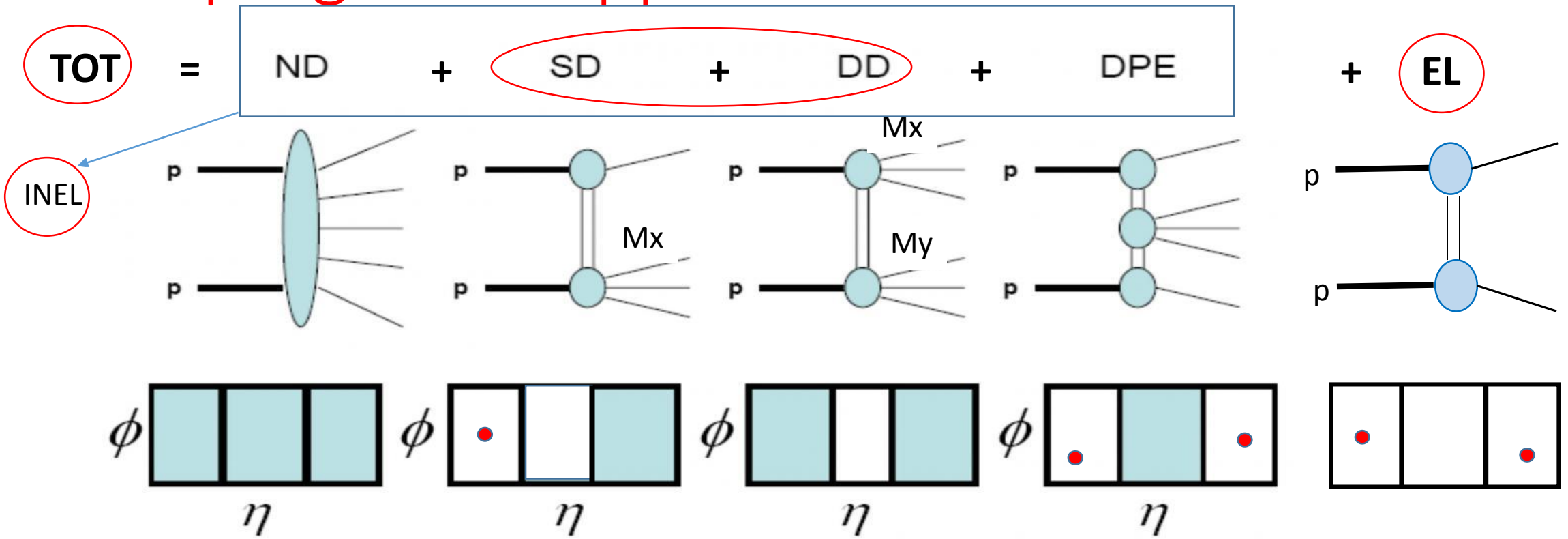


CR energies determined through hadronic MC simulation of shower development

Shower development dominated by forward, soft QCD interactions

Input from Forward Physics measurements at LHC is very valuable

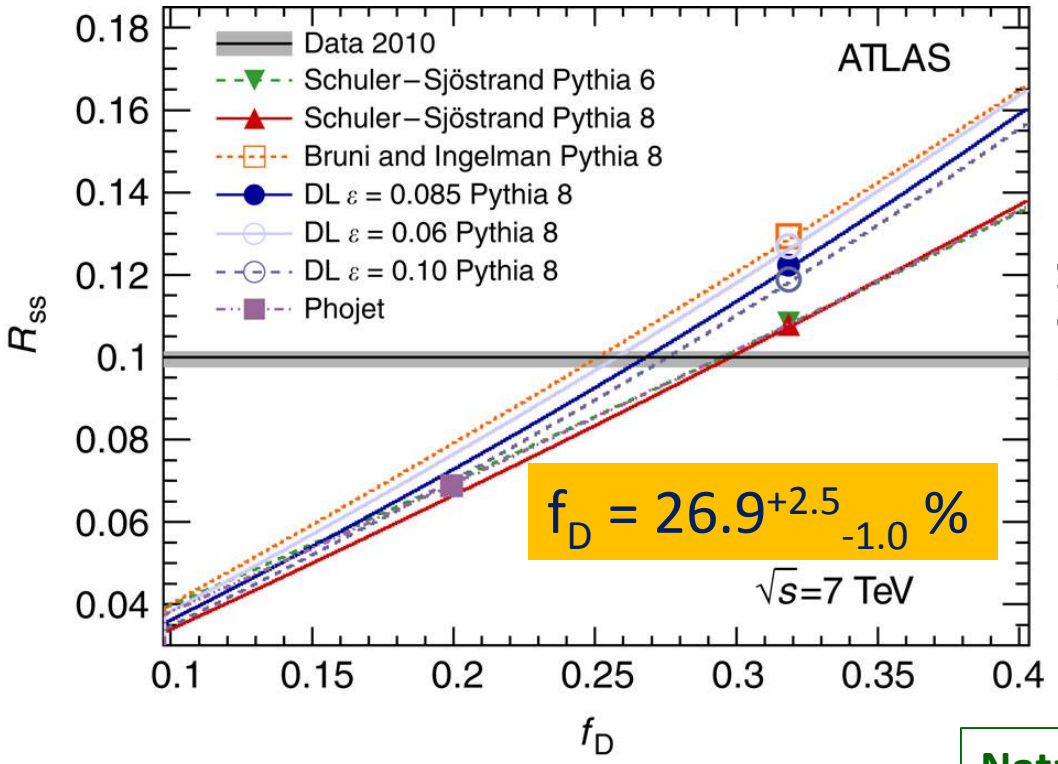
ATLAS program on pp cross section measurements

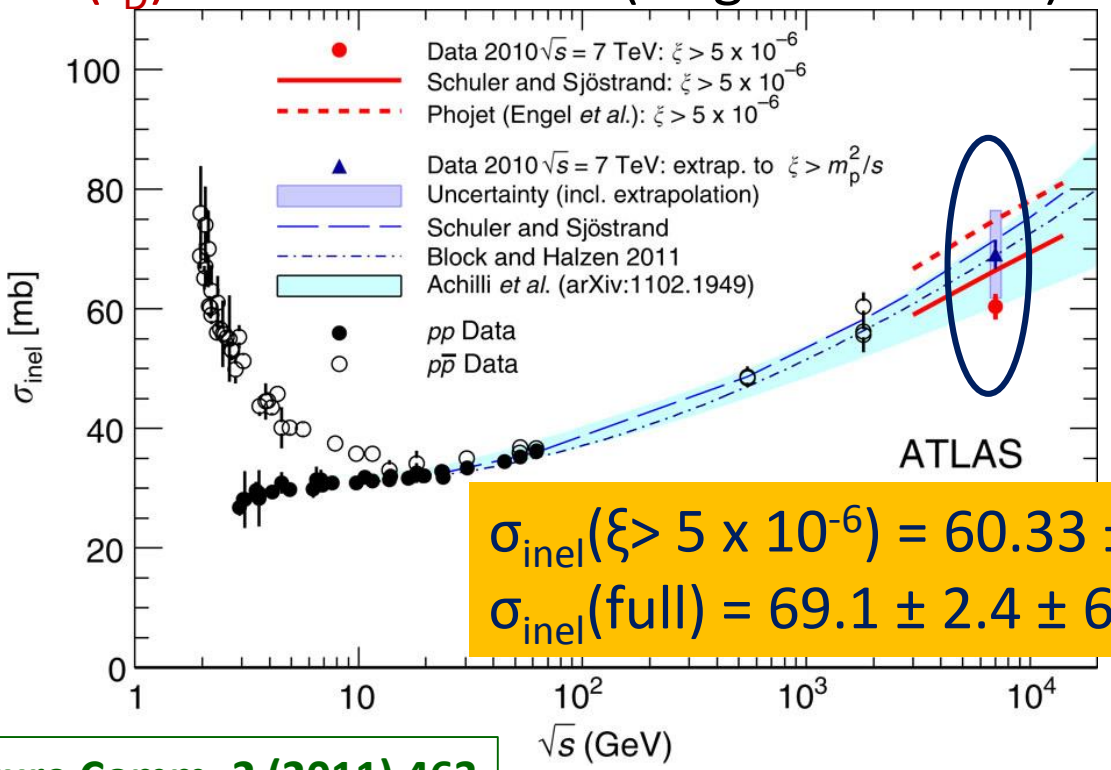


- measure the total pp cross section (not calculable within QCD) → input for cosmic-rays
- determine the different contributions to the total cross section
  - **Complete picture only if one measure σ_{inel} σ_{el} σ_{tot} together with diffractive contribution**
- Provide good understanding of the soft-processes
- Help tuning Monte Carlo generators with hard+soft processes → input for cosmic-rays

Measurement of the inelastic cross section @ 7 TeV

- Direct measurement of σ_{inel} of interest for modelling high-energy cosmic ray showers
- Measured in fiducial region $\xi = M_x^2/s > 5 \times 10^{-6}$ (MBTS trigger) and extrapolated to full kinematic range
- Fraction of diffractive-to-inelastic events (f_D) also determined (single-side veto) => MC tune





large extrapolation uncertainty: direct measurement preferrable !

Nature Comm. 2 (2011) 463

ATLAS measurement of σ_{tot} @ 7 TeV

|t| larger than Coulomb-Nuclear interference region (ATLAS: 0.01<|t|<0.1 GeV^2): Optical Theorem

$$\sigma_{tot}^{\ 2} = \frac{16\pi(\hbar c)^2}{1+\rho^2}\left.\frac{d\sigma_{el}}{dt}\right|_{t\to 0}$$

$$\frac{d\sigma_{el}}{dt} = \frac{1}{16\pi}\left|f_N(t) + f_C(t)e^{i\alpha\phi(t)}\right|^2$$

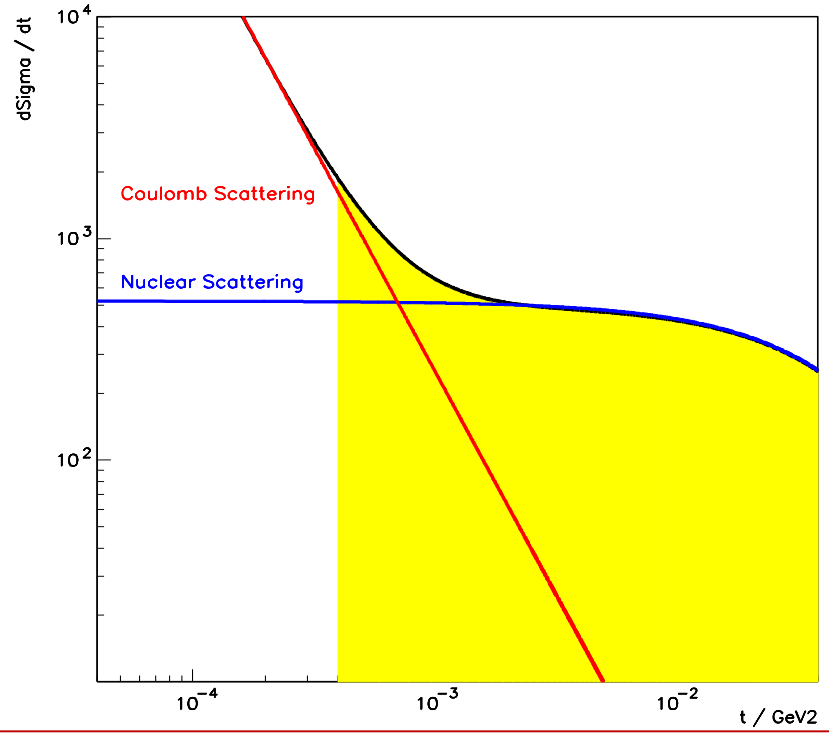
$$f_C(t) = -8\pi\alpha\hbar c\frac{G^2(t)}{|t|}$$

$$f_N(t) = (\rho+i)\frac{\sigma_{TOT}}{\hbar c}e^{-B|t|/2}$$

measure elastic spectrum and luminosity simultaneously

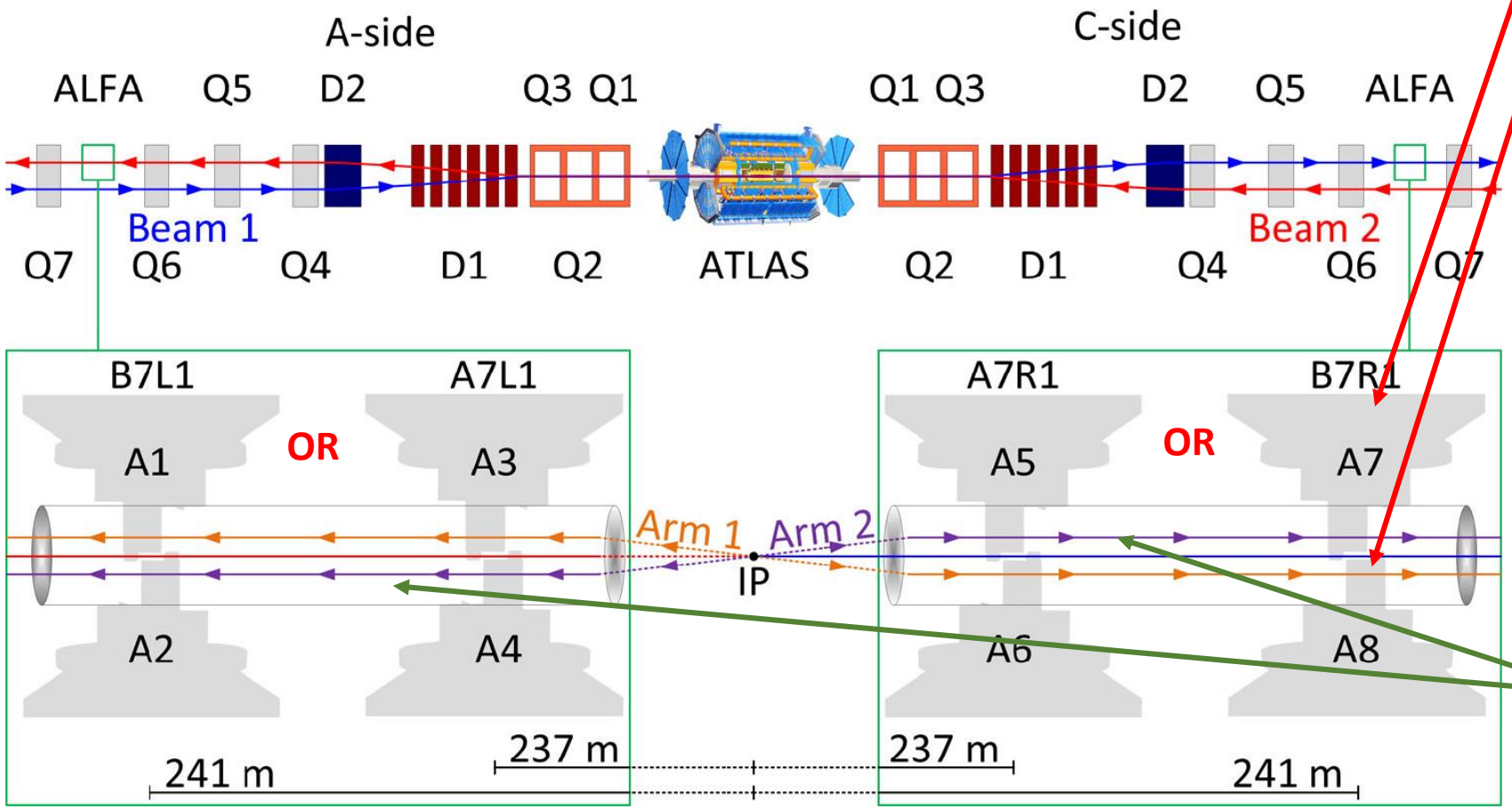
down to the Coulomb-Nuclear interference region (|t| ~ 10^{-3})

(see future perspectives)



Nucl. Phys B 889 (2014) 486

The ALFA subdetector in ATLAS



- ALFA Roman-Pots located 240 m from IP
- Scintillating-fibers detectors
  - Approach 5 mm to beam
- Special optics dedicated to elastic scattering measurement
  - High-β* (90 m)
  - Parallel-to-point focusing in vertical plane
  - Phase-advance 90˚
- 800k «elastic» events
  - back-to-back (A/C-sides) trigger

Principle of the measurement

- Measure t-spectrum ($d\sigma_{el}/dt$) from the track positions in ALFA

$$\begin{pmatrix} y \\ \theta_y \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} y^* \\ \theta_y^* \end{pmatrix}$$

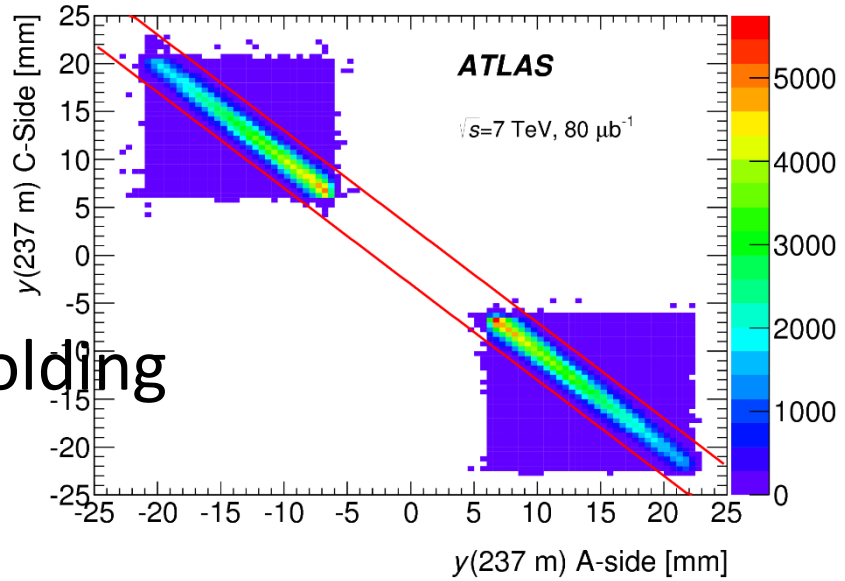
In ALFA | Beam transport matrix | At the IP

Parallel-to-point focusing

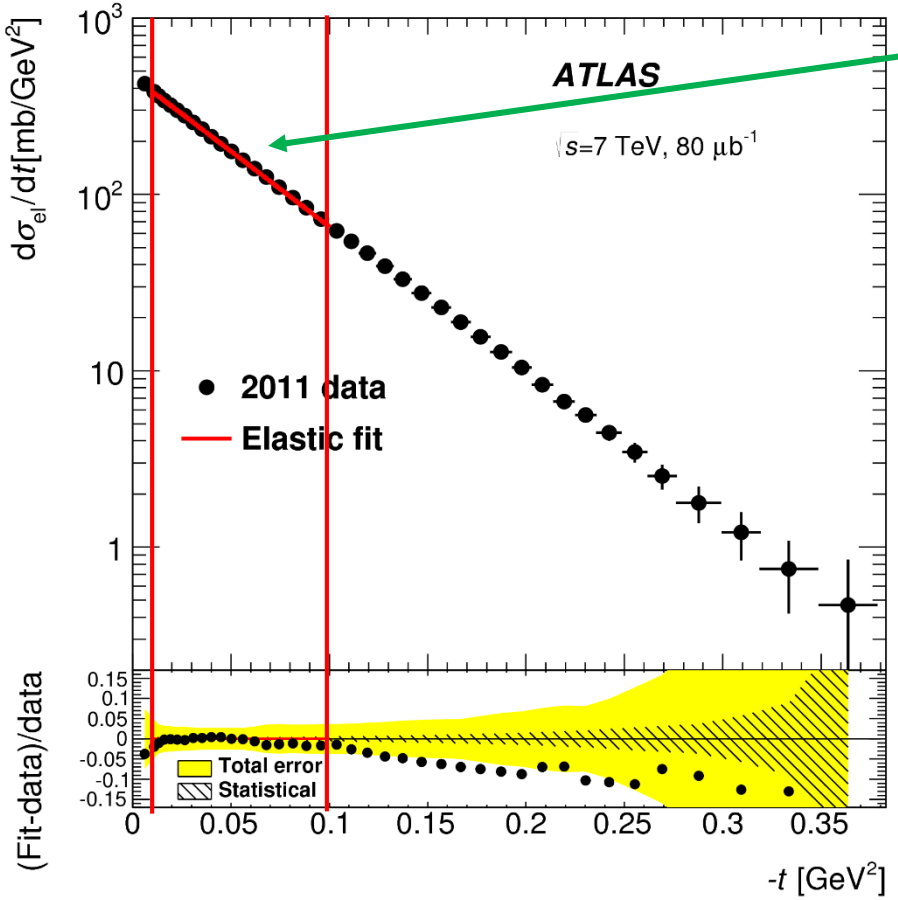
$$\theta_y^* = \frac{y}{M_{12}}$$

$$t = -\left(p\theta^*\right)^2$$

- Back-to-back topology selected (elastic signature)
- Anti-elastic signature for background subtraction
- Pythia8 elastic generator and beam-transport + unfolding
- Efficiency with data-driven approach



Total cross section result



- Fit in $0.01 < -t < 0.1$ GeV^2 including CNI term
  - Region where deviations from exponential behaviour are small
  - All experimental systematic uncertainties included in the fit

$\sigma_{tot} = 95.4 \pm 1.4$ mb

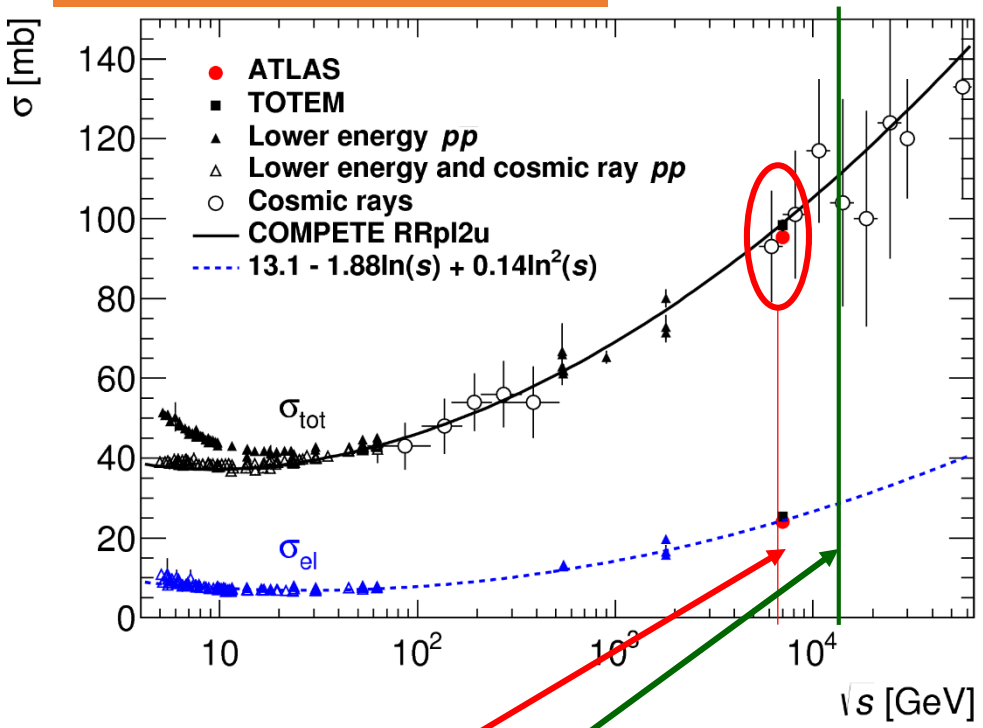
$B = 19.73 \pm 0.29$ GeV^{-2}

  - Systematic uncertainties include contribution from extrapolation to t->0 (0.4 mb and 0.17 GeV^{-2})

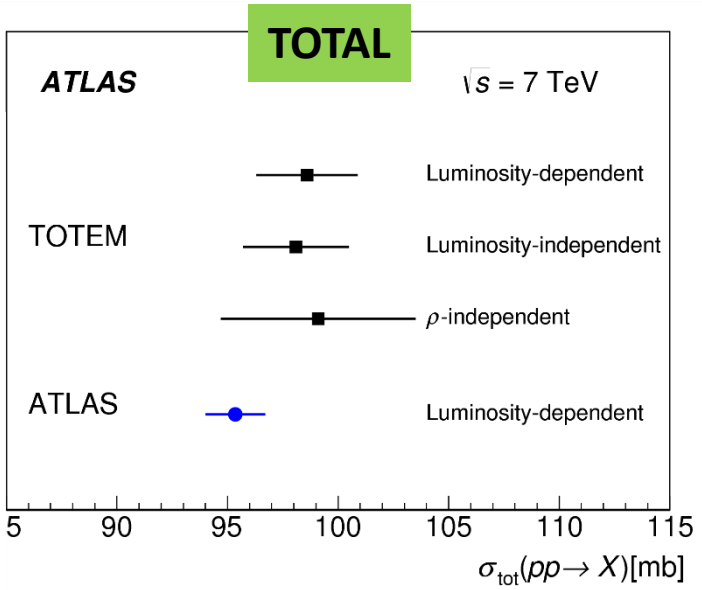
Nucl. Phys B 889 (2014) 486

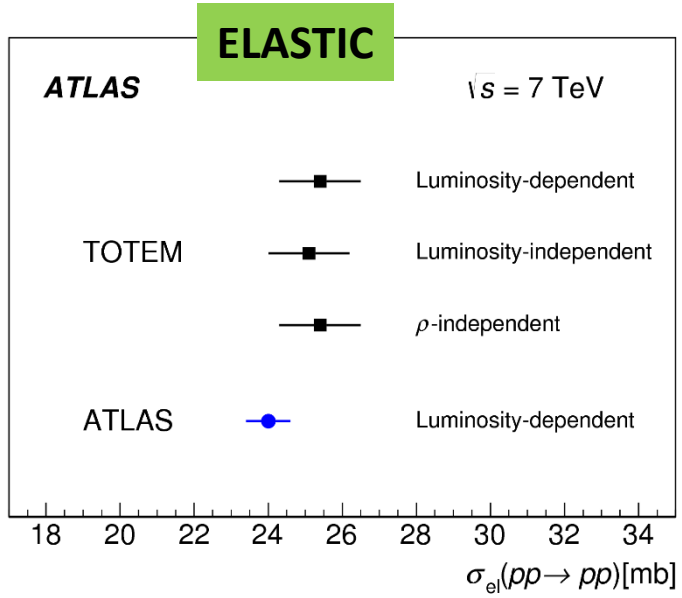
Picture of the ATLAS pp cross section measurements

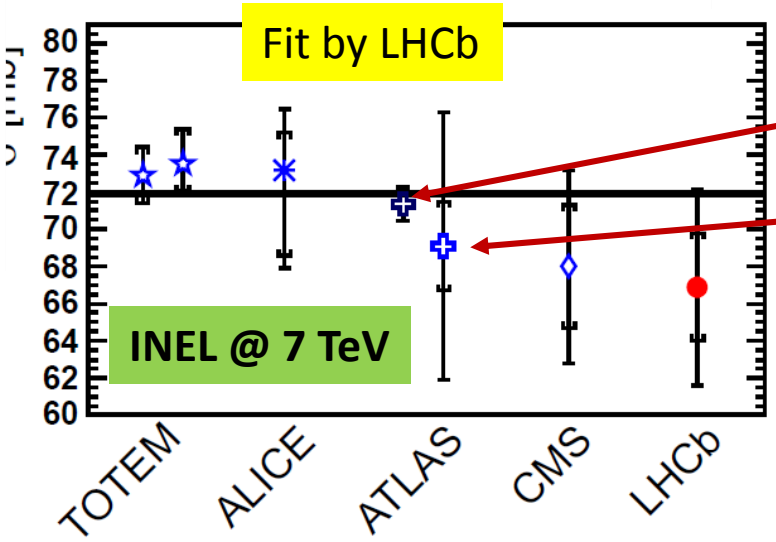
σ_{el} = 24.0 ± 0.6 mb
σ_{inel} = 71.3 ± 0.9 mb



7 TeV at the border of CR measurements
At 13 TeV fully inside CR, first time in pp !







From elastic scattering (ALFA)

Direct measurement (slide 6)

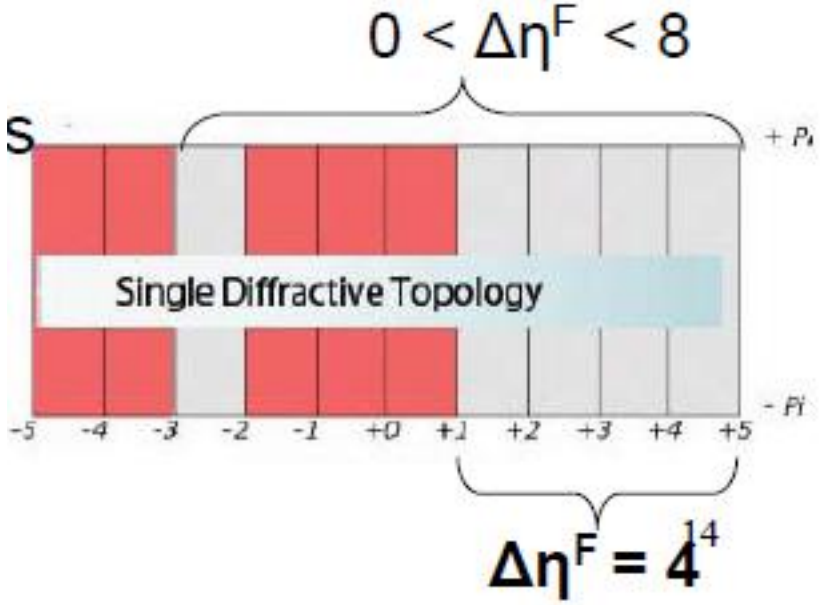
Discussion about cross section measurements

- ATLAS performed a wide range of pp cross section measurements @ 7 TeV
- Two independent measurements of σ_{inel} with different techiques and data samples and kinematic ranges
  - Comparing them $\sigma_{inel}(\xi=M_x^2/s < 5 \times 10^{-6}$ i.e. $M_x < 15.7$ GeV) = 11.0±2.3 mb is larger than predicted by PYTHIA and PHOJET
- Comparison with TOTEM:
  - σ_{tot} agreement within 1.3σ
  - σ_{el} agreement within 1.1σ
- Including data at lower (pp collider) and higher (cosmic rays) energies:
  - ATLAS measurement is 2σ below the fit with $\ln^2(s)$ dependence (COMPETE)
    - perfect agreement with models predicting slower energy dependence

Differential inelastic cross section measurement using Rapidity Gaps (I)

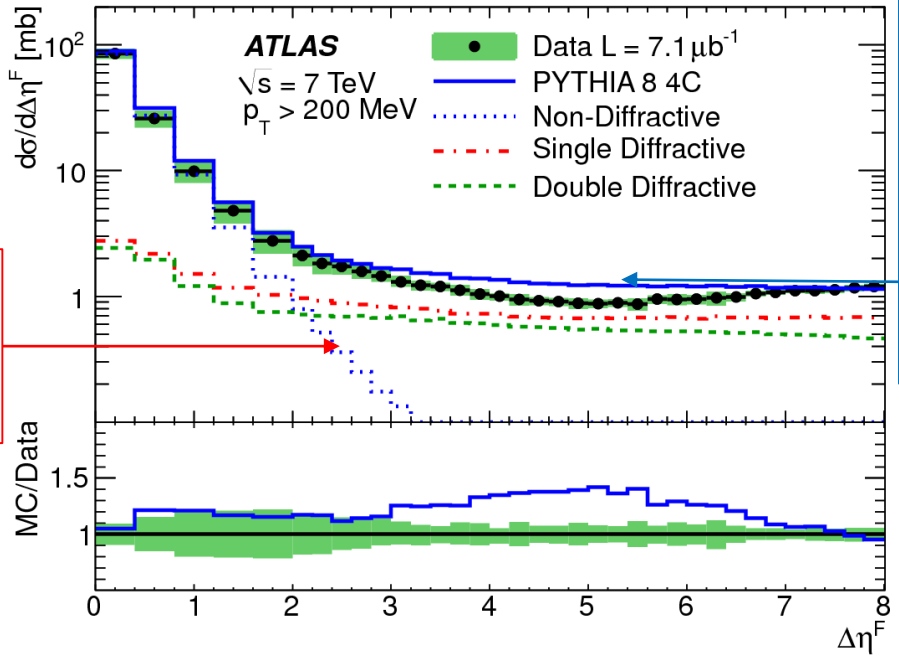
- Rapidity gaps useful tool for ND-to-Diffractive separation
  - Inner Detector (tracks with pT>200 MeV, $|\eta|<2.5$) & Calorimeters (energy deposits above noise threshold, $2.5<|\eta|<4.9$) used for rapidity gap definition
  - Rapidity-gap in η-rings of size $\Delta\eta^F$
  - $0 < \Delta\eta^F < 8 \iff 10^{-6} < \xi < 10^{-2} \iff 7\ \text{GeV} < M_x < 700\ \text{GeV}$
- ND events have $\Delta\eta^F \sim 0$
  - Test hadronization fluctuations description in MC's

    leading to $\Delta\eta^F > 0$
- Diffractive events populate large $\Delta\eta^F$ bins
  - All MC's predicts $d\sigma/d\Delta\eta^F \sim$ const at large $\Delta\eta^F$



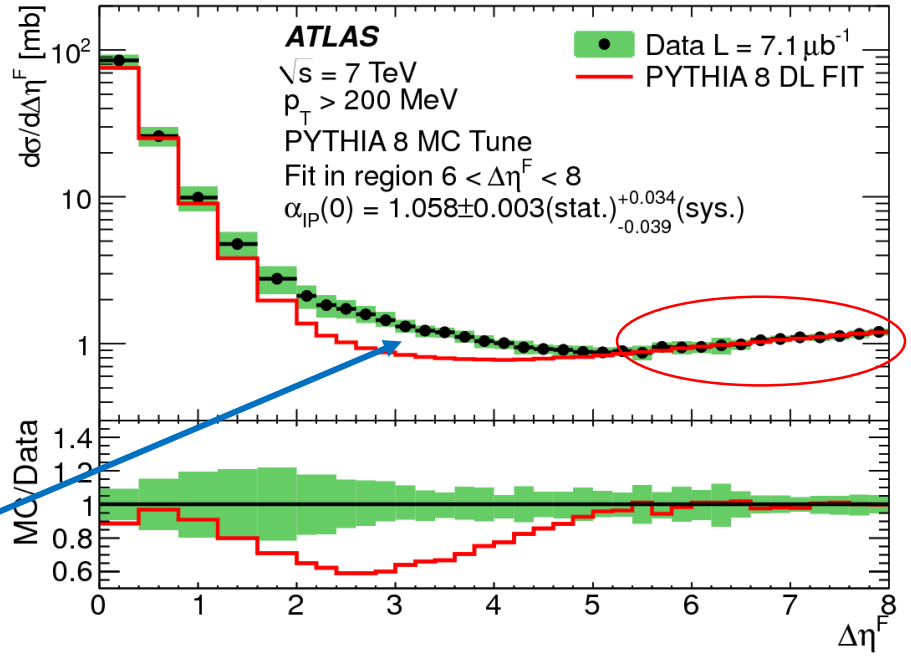
Eur. Phys J. C (2012) 72:1926

Differential inelastic cross section measurement using Rapidity Gaps (II)



Hadronization Fluctuations for ND events

- Fully corrected data (unfolding)
- Pythia and Phojet overestimate σ_{inel}
- MC's describe trend, but not details
- Predicted plateau at large $\Delta\eta^F$ (diffraction) seen. Still raise at high $\Delta\eta^F$ needs MC tuning.

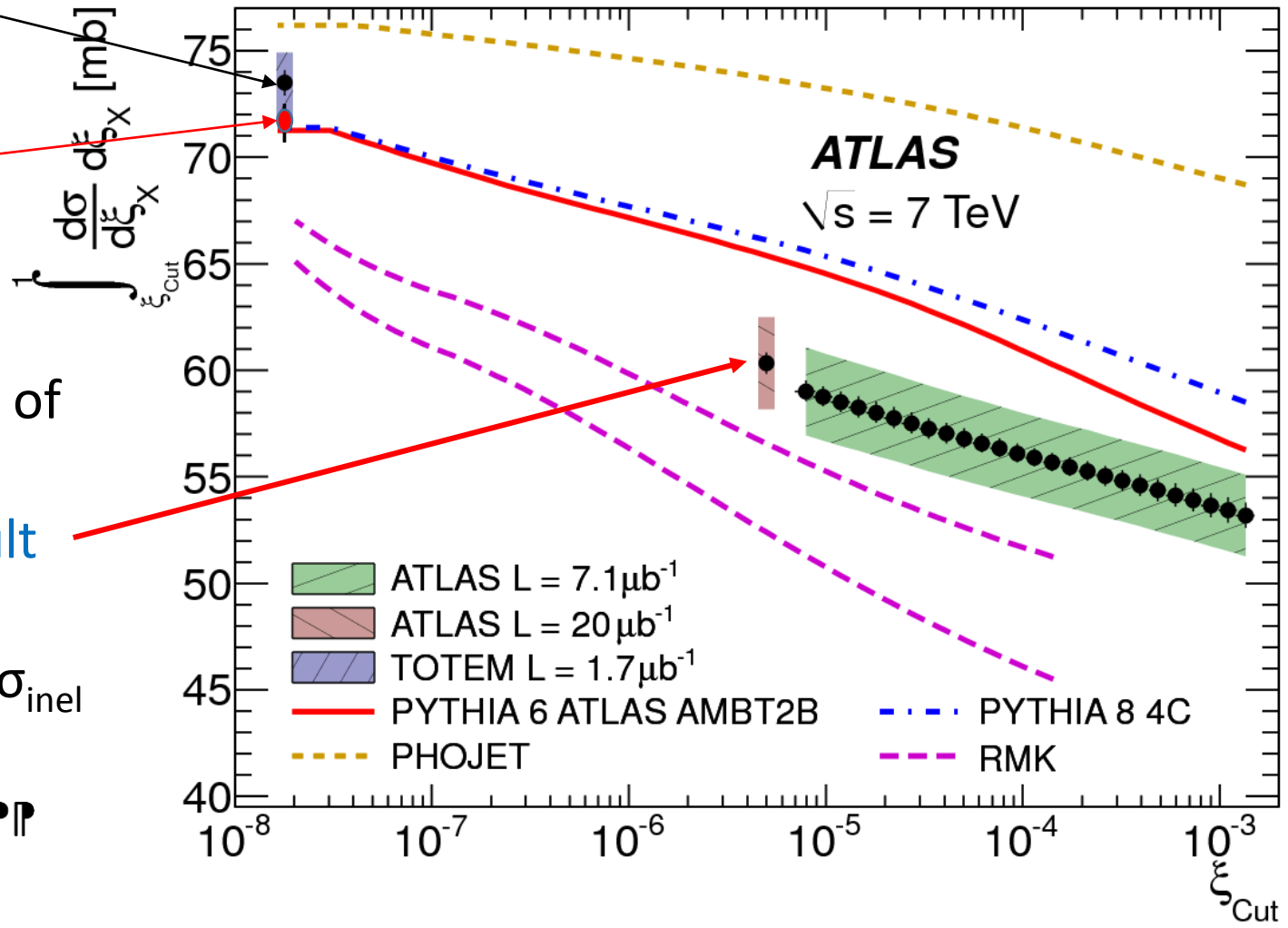


- Raise at $\Delta\eta^F > 5$ described by Pythia8 with Donnachie-Landshoff Pomeron flux
  - $\alpha_{IP}(0) = 1.058\ (40)$
- Poor description in intermediate $\Delta\eta^F$ range
  - Missing CD ? Hadronization fluctuations ?

Total inelastic cross section measurement using Rapidity Gaps

TOTEM measurement
(full ξ-acceptance)

ATLAS measurement
from σ_{TOT} and σ_{EL}
(full ξ-acceptance)
(see slide 13)

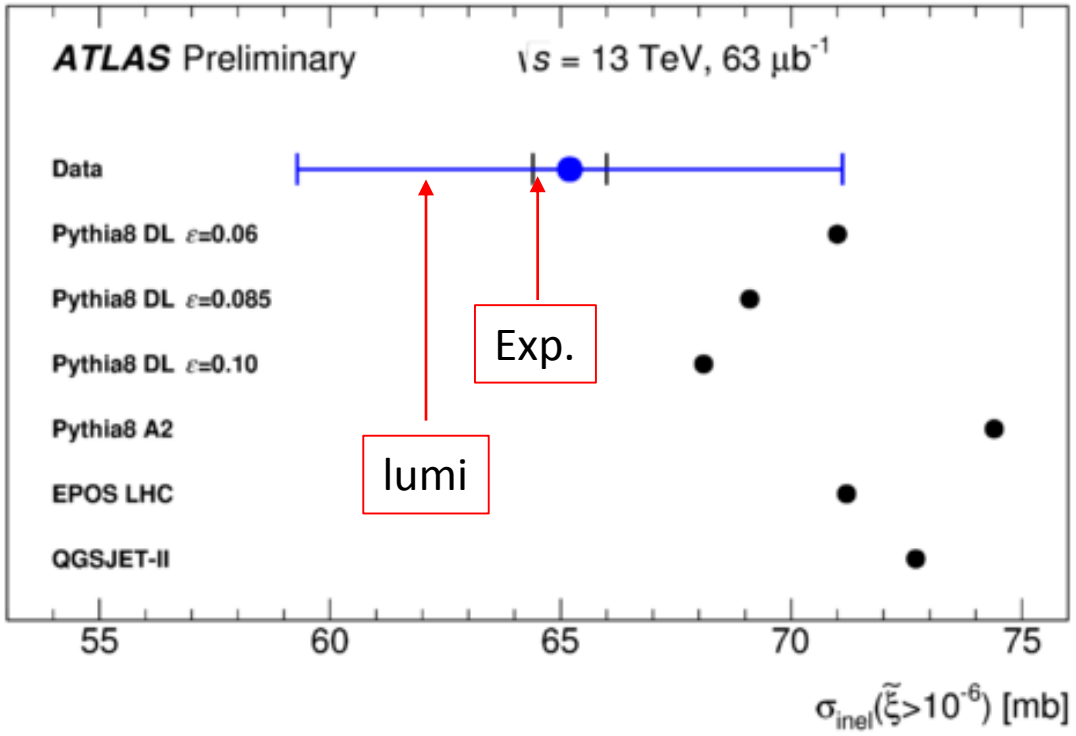


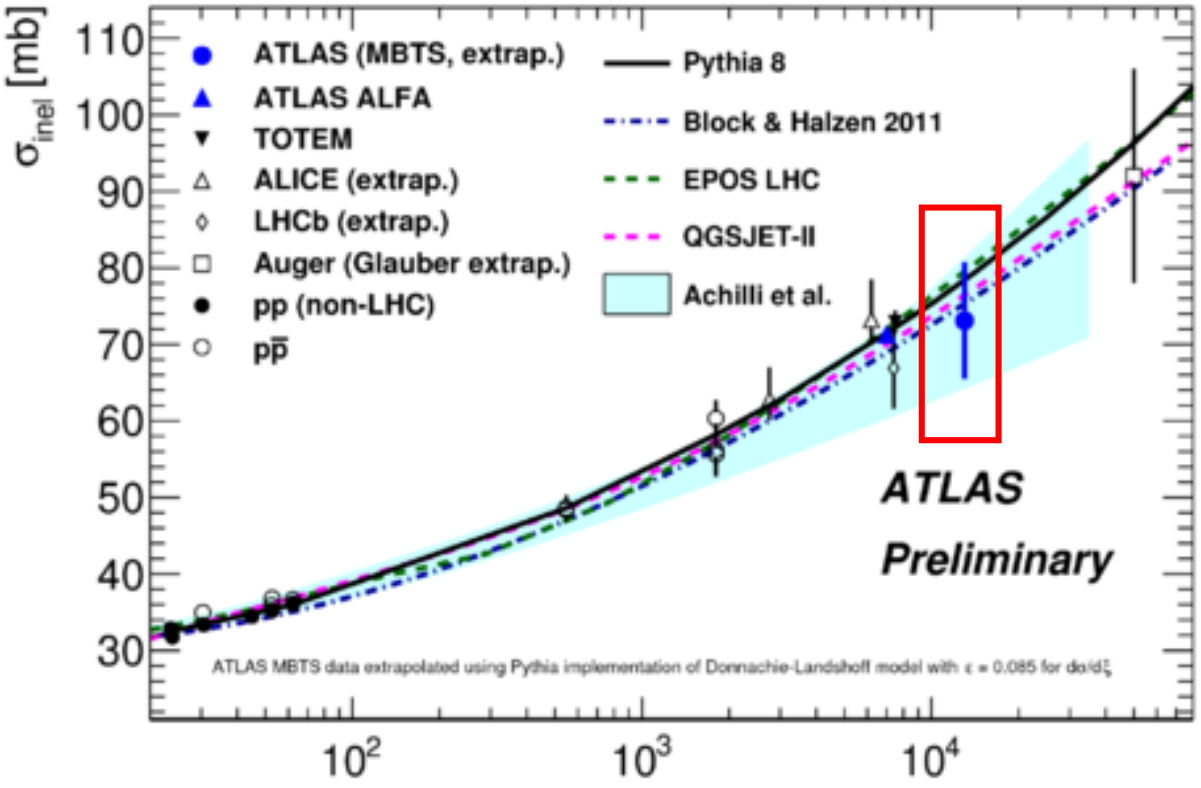
- Another independent measurement of $\sigma_{inel}(\xi>\xi_{cut})$ i.e. $\sigma_{inel}(\Delta\eta^F < \Delta\eta^F_{cut})$
- Good agreement with previous result ($\xi>5\ 10^{-6}$, see slide 6)
- PYTHIA and PHOJET underestimate σ_{inel} at low ξ (already discussed)
- Ryskin-Martin-Khoze (RKM) with ℙℙℙ model better describe rise at low ξ

New Measurement of the inelastic cross section @ 13 TeV

- First LHC measurement with new data (summer 2015) at 13 TeV : L=63±6 μb^{-1}
- Measured in fiducial region $\xi=M_x^2/s > 10^{-6}$ (M_x>13 GeV); extrapolated to full kinematic range
- Determined fraction of diffractive-to-inelastic events $f_D \in [25\text{-}32]\%$ => MC tune

$\sigma_{inel}(\xi>10^{-6}) = 65.2 \pm 0.8 \pm 5.9$ mb





$\sigma_{inel}(full) = 73.1 \pm 0.9 \pm 6.6(lum) \pm 3.8(extr)$ mb

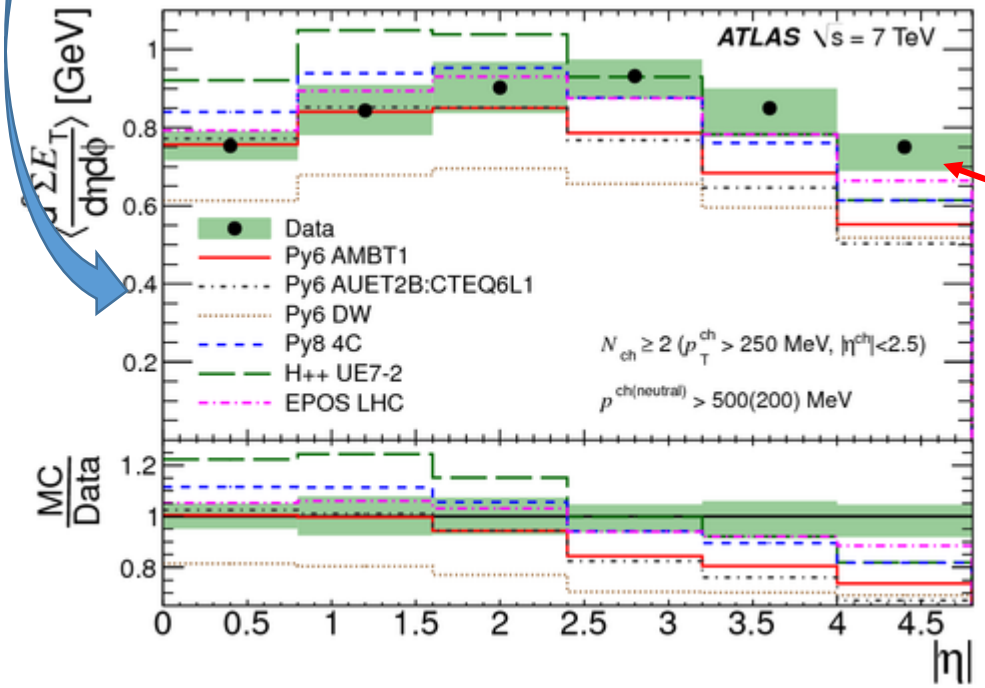
Transverse energy as a function of pseudorapidity

- Measurement of sum of transverse energy $\Sigma(E_T)$ as a function of η ($|\eta| < 4.8$)
- Full ATLAS acceptance, including forward region (calorimeters)
- Aim: tune phenomenological models used by MC to describe non-perturbative QCD processes
  - Inclusive pp interactions (minimum-bias trigger)
  - «underlying event»: soft-interactions (accompanying hard-process) due to partons not involved in the hard-scattering (di-jet trigger, ensure that a hard-process occurred)
- Comparison with MC generators including EPOS primarly used to simulate cosmic showers
- Low luminosity data-samples used to minimize multiple proton-proton interactions (pile-up)

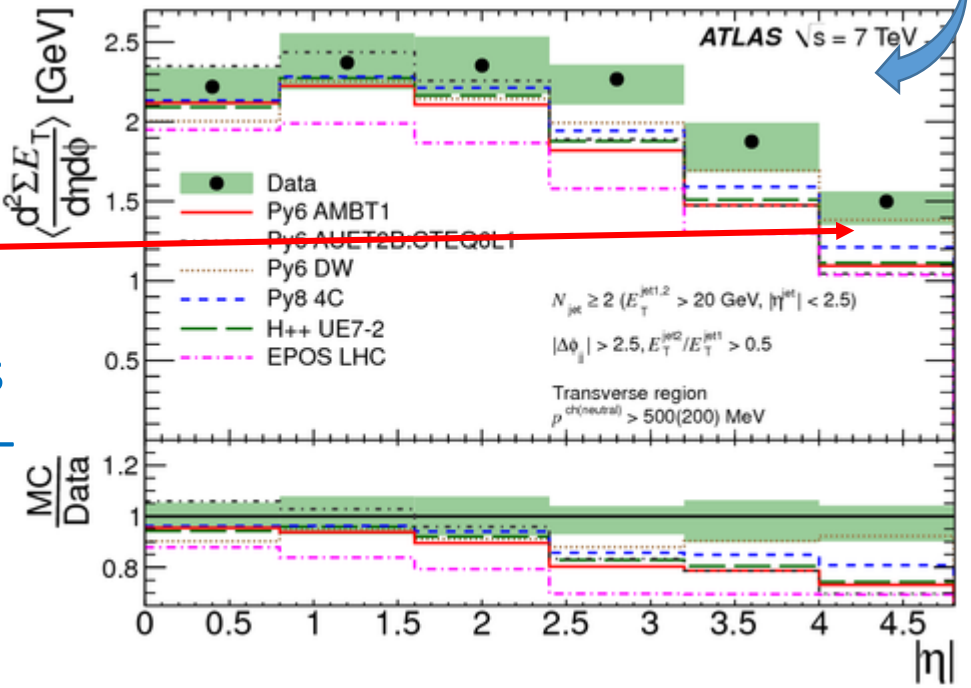
JHEP 11 (2012) 033

Transverse energy density $< \frac{d^2\Sigma E_T}{d\eta d\phi} >$

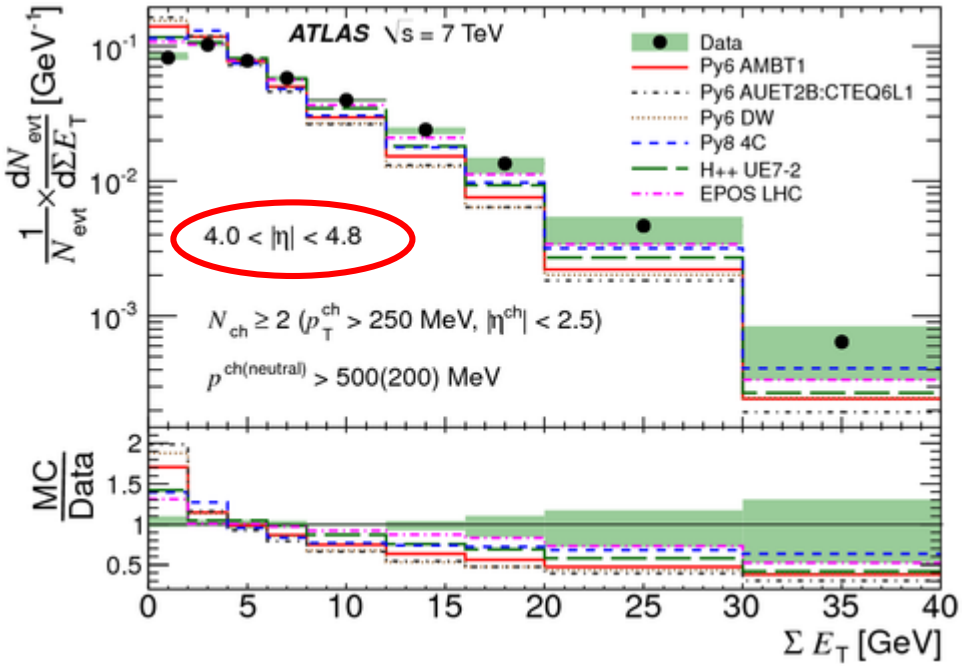
- Mean transverse energy per unit (η,ϕ)
  - Minbias: include particles at any ϕ
  - Di-jet: only particles in azimuthal region transverse to leading-jet (exclude hard-process)



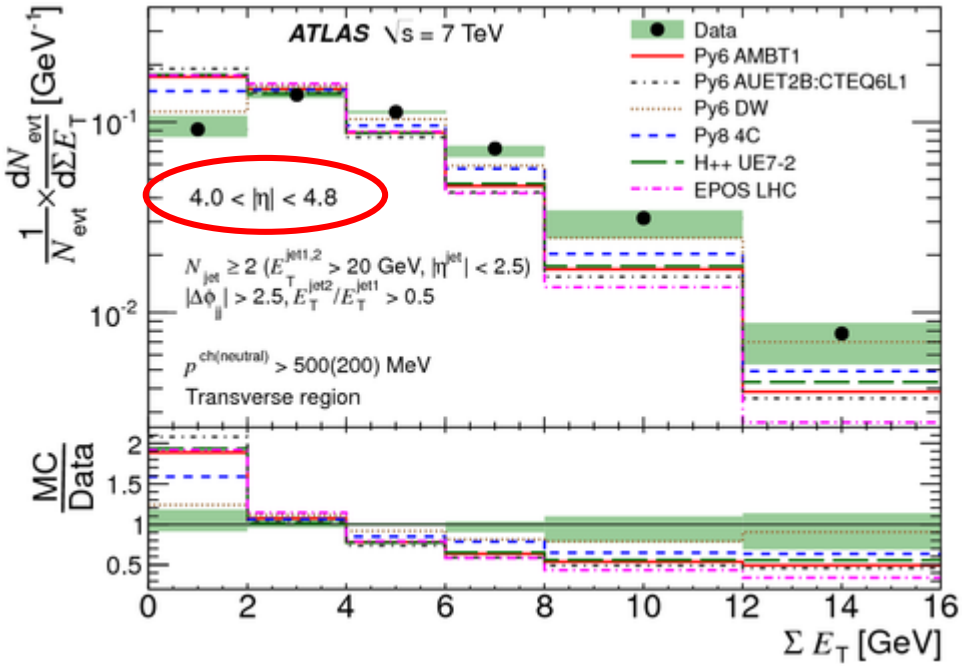
- All MC too low in forward direction
- Best EPOS in minbias sample, but not in di-jet



Total transverse energy



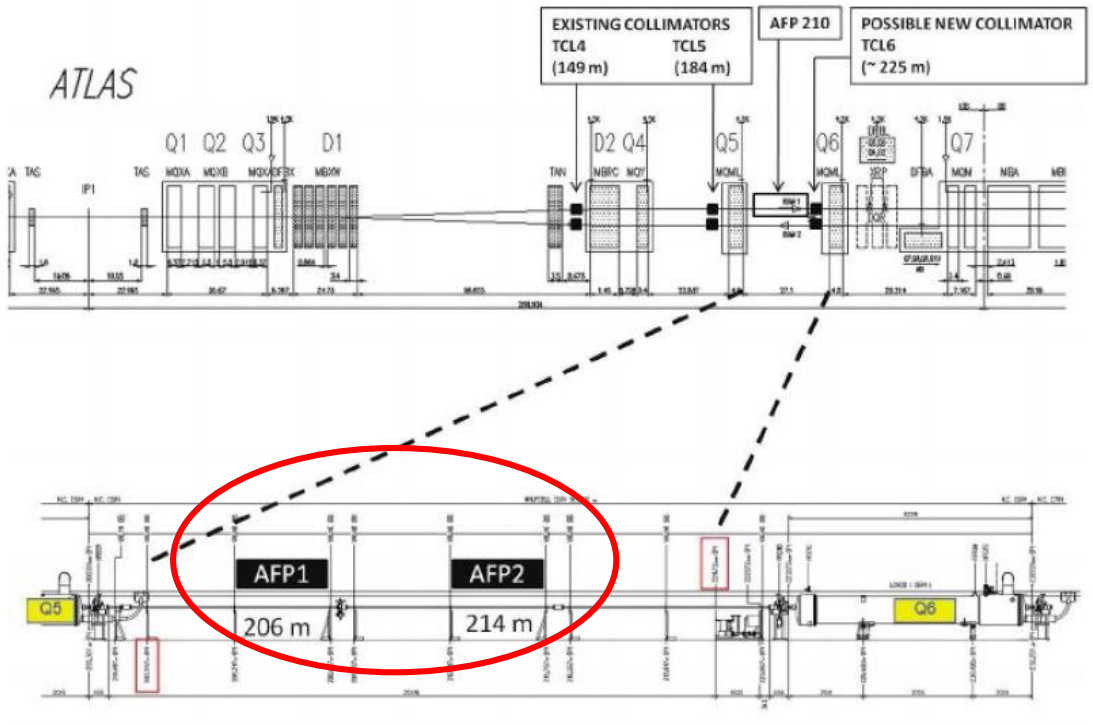
$$\frac{1}{N_{evt}}\frac{dN_{evt}}{d\Sigma E_T}$$

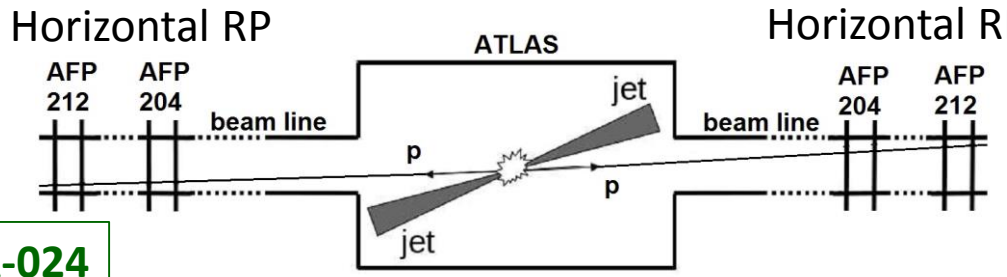


- In both samples, all MC overestimate (underestimate) the distribution at low (high) transverse energy
- Overall: EPOS best describes minimum-bias data, but not di-jet sample

Future perspectives: ATLAS Forward Proton Detector (AFP)

- Horizontal Roman Pots located at 210 meters from ATLAS IP (2 stations in each side)
- Aimed to a wide program in diffractive physics
- Complemetary to ALFA in terms of acceptance
- Foreseen low-luminosity program, but high-luminosity possible (both low and high β*)
- Approved in June 2015 by ATLAS & LHC
- Installations:
  - 1-st arm in 2015-16 winter shutdown
  - 2-nd arm in 2016-17 winter shutdown



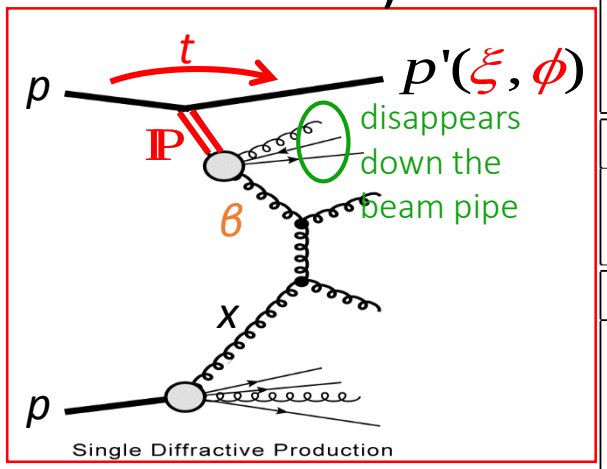


CERN-LHCC-2015-009 ; ATLAS-TDR-024

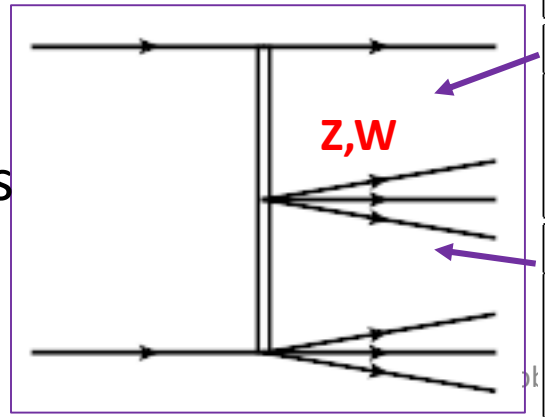
The physics case: single-proton tag (single arm)

- Soft and hard single-diffraction
  - Interest for cosmic rays community
- Double-arm (double-diffraction):

  see backup slides



- LHC conditions:
  - High-β* (start-up)
  - Normal LHC optics
  - Low pile-up (μ)



Analysis	Motivation	$\int Ldt$ [pb^{-1}]	Optimal μ
Soft Single Diffraction with AFP0+2			
$d\sigma/dt$, $d\sigma/d\xi$, t-Slope vs. ξ, $dN^{\pm}/dp_T$ vs. t and ξ	Saturation, MC tuning, Cosmic Ray physics	1	$\mu \sim 0.01$
Single Diffractive jet Production [21]			
σ, rapidity gap, Jet structure and p_T, event shape (MPI [21]); vs. t, ξ, and β	gap survival probability, Pomeron structure	10 – 100	$\mu \sim 1$
Single Diffractive jet-gap-jet Production [22, 23, 24]			
σ, central gap distribution, Jet p_T; vs. t, ξ, and β	observation of a new process, test of BFKL dynamics	1 – 100	$\mu \sim 1$
Single Diffractive Production of γ + jet [25]			
σ, rapidity gap, Jet structure and p_T, Photon p_T, event shape (MPI); vs. t, ξ, and β	observation of a new process, mechanism of hard diffraction, gap survival probability, Pomeron structure	10 – 100	$\mu \sim 1$
Single Diffractive Z Production			
σ, rapidity gap, charge-asymmetry; vs. t, ξ, and β	gap survival probability, Pomeron structure	10 – 100	$\mu \sim 1$
Single Diffractive W Production			
σ, rapidity gap; vs. t, ξ, and β	gap survival probability, Pomeron structure and flavor composition	10 – 100	$\mu \sim 1$

Future perspectives: cross section measurements with ALFA

- Data already available at 8 TeV at β*=90 m (and β*=1000 m)
  - Luminosity-dependent analysis in adavanced stage for β*=90 m
  - Luminosity measurement already available for both cases.
- Perspectives for Run II @ 13 TeV
  - Consolidation of ALFA detector performed during long shutdown
    - RF-protection, Roman-Pots placement
  - Elastic and diffractive program at low luminosity foreseen at sqrt(s) = 13 TeV

conclusions

- Wide forward physics program performed by ATLAS
- Wide set of cross-section measurements at 7 TeV (total, elastic, inelastic, diffractive fraction)
- First LHC measurement of inelastic cross-setion at 13 TeV !
- Energy flow in the forward direction
  - (Forward Jet production, not described in this talk)
- Results are of high interest for the Cosmic Rays community
- Phsyics program will be extended in Run 2 to higher energy (cross sections with ALFA at 13 TeV) and to unexplored kinematic regions and including new processes (AFP)

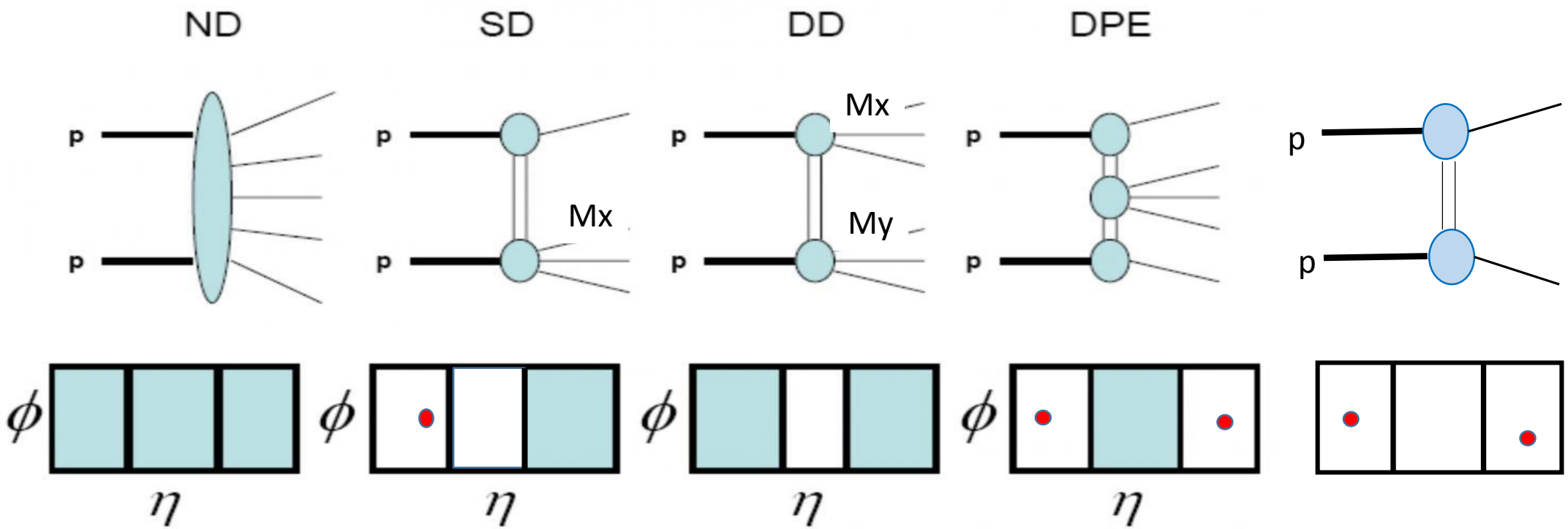
backup

ATLAS program on pp cross section measurements

95.4 ± 1.4 mb **INEL = 71.3 ± 0.9 mb (74.7%)** **24.0 ± 0.6 mb (25.3%)**

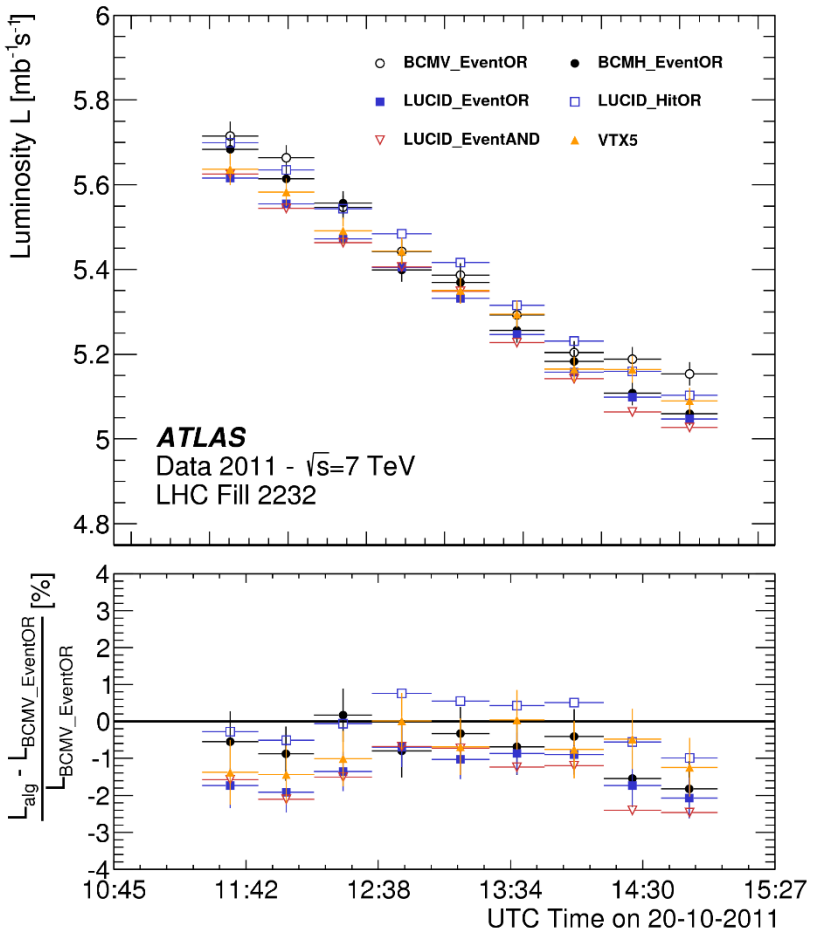
TOT = **ND** + **DIFF** + **EL**

DIFF/INEL = $f_D = 26.9^{+2.5}_{-1.0}$ % (σ_{DIFF} ~ 19 mb)



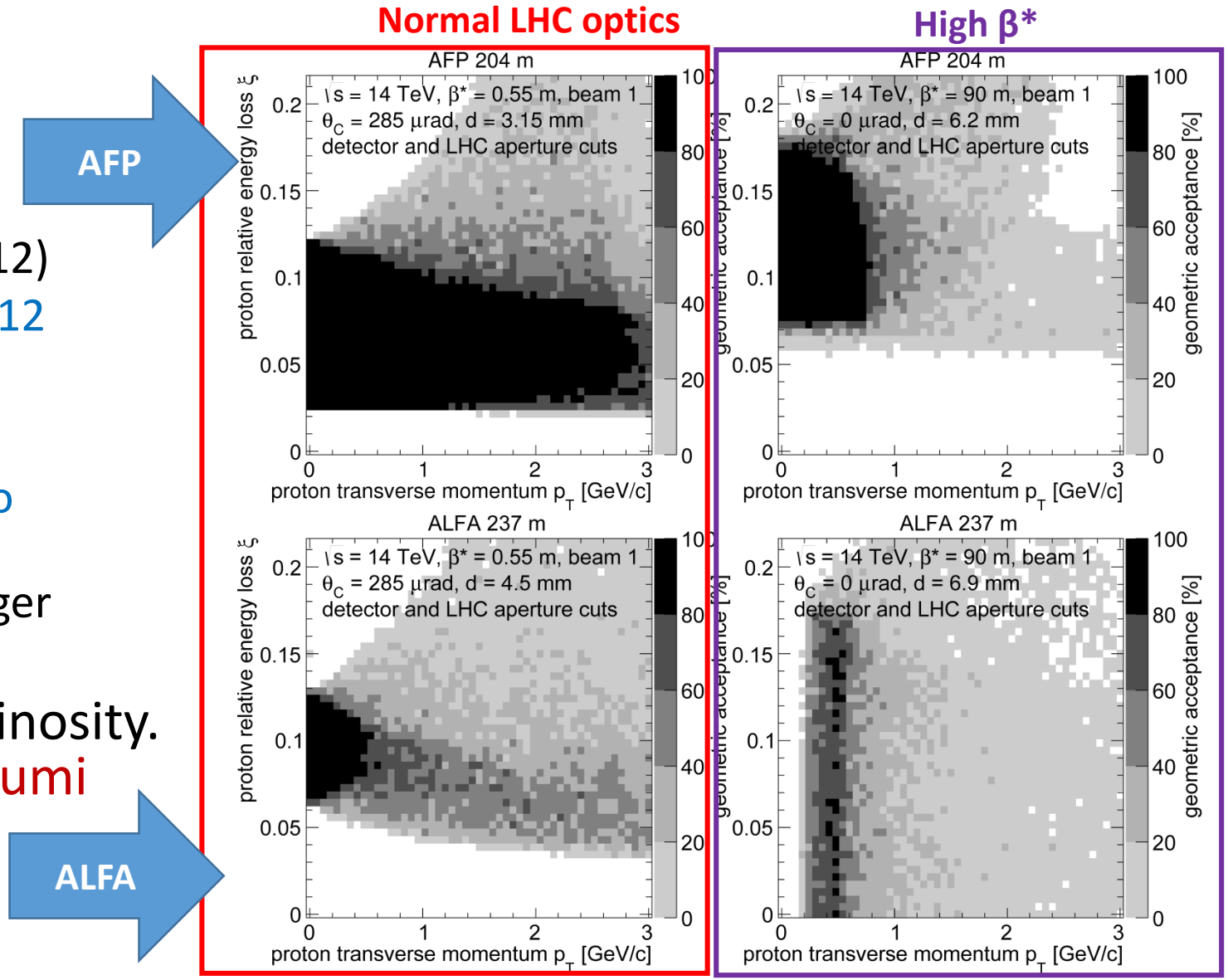
Luminosity determination

- Crucial ingredient for normalization (t-spectrum to $d\sigma_{el}/dt$)
- Systematic uncertainty enters (*halved*) in the overall systematic error
- ATLAS strategy: redundant measurement
  - different detectors and algorithms (LUCID, BCM, Vertex-Counting)
  - Proved to be winning strategy both at high and low luminosity
- $L = 78.7 \pm 0.1_{stat} \pm 1.9_{sys}\ \mu b^{-1}$
- Systematic uncertainty 2.3%
  - Dominated by VdM calibration systematics
  - About twice smaller than CMS-TOTEM
  - Still dominant contribution



AFP and ALFA complementarity

- Normal LHC Optics (β* = 0.55 m)
  - ALFA: limited acceptance in ξ (0.06-0.12)
  - AFP: large acceptance for 0.02 < ξ < 0.12 over large p_T range
- High- β* (90 m)
  - ALFA spans large ξ-range down to 0 (to measure elastic scattering at small-t)
  - AFP: ξ-acceptance shifted towards larger values
- Note: ALFA can run only at low-luminosity. Extensions to AFP program at high lumi possible.



AFP detectors and status

- Roman pots (replica of TOTEM ones)
  - Status: design finalized, order done, first station by October
- Tracking detector: edgeless 3-D Silicon Pixel Tracker (derived from already working ATLAS IBL technology)
  - Crucial is spatial resolution: 10 (30) µm in x(y) and radiation hardness
  - Measured efficiency >98%
  - Will approach to about 4 mm from the beam (depends on optics)
- Time-of-flight required for background rejection only at high µ
  - 10 ps time-resolution, large coverage and efficiency, segmentation for multi-proton measurements, trigger-capability, radiation-hard
  - Micro-Channel Plate Multi-Anode PMT

AFP: the physics case with double-proton tag (2 arms)

Analysis	**Motivation**	$\int Ldt$ [pb^{-1}]	**Optimal μ**
Soft Central Diffraction with AFP2+2			
$d\sigma/dt_{1,2}$, $d\sigma/d\xi_{1,2}$, t-Slope vs. ξ, Mass M and y of the central diffractive system, ϕ_1 vs. ϕ_2, $dN^{\pm}/dp_T$; vs. $t_{1,2}$, $\xi_{1,2}$, M.	general understanding of DPE processes	1	$\mu \sim 0.1$
Central Diffractive jet Production (DPEjj) [28]; see also Sect. A			
$d\sigma/dt_{1,2}$, $d\sigma/d\xi_{1,2}$, t-Slope vs. ξ, $d\sigma/dp_T^{jet}$, Mass M and y of the central dijet system, ϕ_1 vs. ϕ_2	gap survival probability for DPE processes, Pomeron structure, general understanding of DPE processes	10 – 100	$\mu \sim 1$
Jet-gap-jet Production [22, 24]			
$d\sigma/dt_{1,2}$, $d\sigma/d\xi_{1,2}$, $d\sigma/dM_{jj}$, central gap distribution, $d\sigma/dp_T^{jet}$, ϕ_1 vs. ϕ_2	observation of a new process, test of BFKL dynamics	10 – 100	$\mu \sim 1$
γ + jet Production			
σ, rapidity gap(s), Jet structure and p_T, Photon p_T; vs. $t_{1,2}$, $\xi_{1,2}$, and M_{jj}	observation of a new process, mechanism of hard diffraction, gap survival probability, Pomeron structure	10 – 100	$\mu \sim 1$

ATLAS Publications: cross sections and energy flow (I)

- Measurement of the Inelastic Proton-Proton Cross-Section at √s = 7 TeV with the ATLAS detector - Nature Commun. 2 (2011) 463
- Measurement of the total cross section from elastic scattering in pp collisions at sqrt(s) = 7 TeV with the ATLAS detector – Nuclear Physics, Section B(2014), pp. 486-548
- Rapidity gap cross sections measured with the ATLAS detector in pp collisions at √s = 7 TeV - Eur. Phys. J. C72 (2012) 1926
- Measurements of the pseudorapidity dependence of the total transverse energy in proton-proton collisions at √s = 7 TeV with ATLAS - JHEP11(2012)033

ATLAS publications: jet production (II)

- Measurement of dijet production with a veto on additional central jet activity in pp collisions at √s=7 TeV using the ATLAS detector - JHEP 1109 (2011) 053
- Measurement of inclusive jet and dijet cross sections in proton-proton collisions at 7 TeV centre-of-mass energy with the ATLAS detector - Eur.Phys.J. C71 (2011) 1512